Application of Fault Detection Techniques to Spiral Bevel Gear Fatigue Data

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APPLICATION OF FAULT DETECTION TECHNIQUES
TO SPIRAL BEVEL GEAR FATIGUE DATA

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Abstract: Results of applying a variety of gear fault detection techniques to experimental data is presented. A spiral bevel gear fatigue rig was used to initiate a naturally occurring fault and propagate the fault to a near catastrophic condition of the test gear pair. The spiral bevel gear fatigue test lasted a total of eighteen hours. At approximately five and a half hours into the test, the rig was stopped to inspect the gears for damage, at which time a small pit was identified on a tooth of the pinion. The test was then stopped an additional seven times throughout the rest of the test in order to observe and document the growth and propagation of the fault. The test was ended when a major portion of a pinion tooth broke off. A personal computer based diagnostic system was developed to obtain vibration data from the test rig, and to perform the on-line gear condition monitoring. A number of gear fault detection techniques, which use the signal average in both the time and frequency domain, were applied to the experimental data. Among the techniques investigated, two of the recently developed methods appeared to be the first to react to the start of tooth damage. These methods continued to react to the damage as the pitted area grew in size to cover approximately 75% of the face width of the pinion tooth. In addition, information gathered from one of the newer methods was found to be a good accumulative damage indicator. An unexpected result of the test showed that although the speed of the rig was held to within a band of six percent of the nominal speed, and the load within eighteen percent of nominal, the resulting speed and load variations substantially affected the performance of all of the gear fault detection techniques investigated.

Key Words: Diagnostics; Failure prediction; Fatigue; Gear

Introduction: Drive train diagnostics is becoming one of the most significant areas of research in rotorcraft propulsion. The need for a reliable health and usage monitoring system for the propulsion system can be seen by reviewing rotorcraft accident statistics. An investigation of serious rotorcraft accidents that were a result of fatigue failures showed that 32 percent were due to engine and transmission components [1]. In addition, governmental aviation authorities are demanding that in the near future the safety record of civil helicopters must match that of conventional fixed-wing turbojet aircraft. This would require a substantial, thirtyfold, increase in helicopter safety statistics. Practi-

cally, this can only be accomplished with the aid of a highly reliable, on-line health and usage monitoring (HUM) system. A key performance element of a HUM system is to determine if a fault exists, as early and reliably as possible. Therefore research is necessary to develop and prove various fault detection concepts and methodologies.

A number of methods have been developed to provide early detection of gear tooth damage. McFadden proposed a method to detect gear tooth cracks and spalls using the instantaneous phase of the demodulated time signal [2]. Stewart devised several time domain discriminant methods of which FM0, a coarse fault detection parameter, and FM4, an isolated fault detection parameter, are the most widely referenced [3]. Lyon [4], and Liu [5], proposed using the instantaneous frequency of the demodulated time signal to detect gear surface pitting. Methods NA4 and NB4 were recently developed at NASA Lewis Research Center to provide early detection of gear tooth surface damage, and continue to react to the damage as it spreads and grows in severity [6].

Verification of these detection methods with experimental data along with a comparison of their relative performance is a crucial step in the overall process of developing a highly reliable HUM system.

In view of the aforementioned, it becomes the object of the research reported herein to determine the relative performance of the detection methods as they are applied to experimental data. Each method is applied to vibration data obtained from a spiral bevel gear fatigue rig at NASA Lewis, where the test gears are run until a fatigue failure occurs. In the test used in this study, a tooth on the pinion developed a pit during the first five and a half hours of the run. The pit was allowed to propagate over a majority of the tooth, resulting in tooth fracture. The performance of each method is discussed, and overall conclusions are presented.

Theory of Fault Detection Methods: All of the methods in this investigation utilized vibration data that was pre-processed as it was collected. To eliminate the noise and vibration that is incoherent with the rotational speed of the spiral bevel test pinion, the raw vibration data was time synchronous averaged immediately after being digitized. During time synchronous averaging, the data was also interpolated to obtain 1024 points over five complete revolutions of the test pinion. Each of the methods below were then applied to the time averaged and interpolated vibration data.

FM0 is formulated to be an indicator of major faults in a gear mesh by detecting major changes in the meshing pattern [3]. FM0 is found by dividing the peak-to-peak level of the signal average by the sum of the amplitudes of the mesh frequency and its harmonics. In major tooth faults, such as breakage, the peak-to-peak level tends to increase, resulting in FM0 increasing. For heavy distributed wear or damage, the peak-to-peak remains somewhat constant but the meshing frequency levels tend to decrease, resulting in FM0 increasing.

FM4 was developed to detect changes in the vibration pattern resulting from damage on a limited number of teeth [3]. A difference signal is first constructed by removing the regular meshing components (shaft frequency and harmonics, primary meshing frequency and harmonics along with their first order sidebands) from the original signal. The fourth normalized statistical moment (normalized kurtosis) is then applied to this difference signal. For a gear in good condition the difference signal would be primarily Gaussian noise, resulting in a normalized kurtosis value of 3 (non-dimensional). When one or two teeth develop a defect (such as a crack, or pitting) a peak or series of peaks appear in the difference signal, resulting in the normalized kurtosis value to increase beyond the nominal value of 3.

A demodulation technique was developed to detect local gear defects such as fatigue cracks, pits and spalls [2]. The basic theory behind this technique is that a gear tooth defect will produce sidebands that modulate the dominant meshing frequency. In this method the signal is band-passed filtered about a dominant meshing frequency, including as many sidebands as possible. The Hilbert transform is then used to convert the real band-passed signal into a complex time signal, or analytic signal. Using the real and imaginary parts of the analytic signal, the instantaneous phase (I.P.) can be estimated from the filtered sidebands. Teeth with a surface failure, or fatigue crack, will cause a lead or lag in tooth contact during meshing, resulting in transient changes in the gear rotation. These transient changes in rotation will dominate the I.P. function. The standard deviation of the I.P. is then calculated over one complete revolution of the pinion to produce a single number in order to quantify the relative variance of the I.P. at each point in the run.

Another technique was proposed in which the rate of change of the instantaneous phase is calculated [4, 5]. This rate of change, or instantaneous frequency (I.F.), is sensitive to the transient rotational speed changes caused by teeth with surface defects, or root cracks, going through the meshing process. The instantaneous frequency and instantaneous phase are different representations of the same physical phenomenon, however the instantaneous frequency is, by definition, more sensitive [4]. A small change in phase within a very short time would result in a correspondingly large change in the I.F. The I.F. is also calculated from a bandpassed portion of the time signal, using the Hilbert transform. The I.F. is found using equation 1 below:

$$f(t) = \frac{b(t)H'[b(t)] - b'(t)H[b(t)]}{2\pi E^2(t)} - f_c \tag{1}$$

where

f(t)	instantaneous frequency (Hz)
b(t)	band passed signal
b'(t)	first derivative of band passed signal
H[b(t)]	Hilbert transform of band-passed signal
H'[b(t)]	first derivative of Hilbert transform of bandpassed signal
E(t)	envelope of bandpassed signal (magnitude of complex time signal)
fc	carrier, or center, frequency of band (primary mesh frequency)

The standard deviation of the I.F. is then calculated over one complete revolution of the pinion to produce a single number in order to quantify the relative variance of the I.F. at each point in the run.

NA4 is a method recently developed at NASA Lewis to not only detect the onset of damage, but also to continue to react to the damage as it increases [6]. Similar to FM4, a residual signal is constructed by removing regular meshing components from the original signal, however, for NA4, the first order sidebands stay in the residual signal. The fourth statistical moment of the residual signal is then divided by the current run time averaged variance of the residual signal, raised to the second power, resulting in the quasi-normalized kurtosis given in equation 2 below:

$$NA4(M) = \frac{N\sum_{i=1}^{N}(r_i - \bar{r})^4}{\left\{\frac{1}{M}\sum_{j=1}^{M}\left[\sum_{i=1}^{N}(r_{ij} - \bar{r}_j)^2\right]\right\}^2} \tag{2}$$

3

where

r   residual signal
r̄   mean value of residual signal
N   total number of time points in time record
i   data point number in time record
M   current time record number in run ensemble
j   time record number in run ensemble

In NA4, the kurtosis is normalized, however it is normalized using the variance of the residual signal averaged over the run up to the current time record number, where NA4 is being calculated. With this method, the changes in the residual signal are constantly being compared to the running average of the variance of the system, or a weighted baseline for the specific system in "good" condition. This allows NA4 to grow with the severity of the fault until the average of the variance itself changes. NA4*, a modified version of NA4, allows the parameter to continue to grow further by "locking" the value of the averaged variance when the instantaneous variance exceeds predetermined statistical limits. As with FM4, NA4 is dimensionless, with a value of 3, under nominal conditions.

NB4 is another parameter recently developed at NASA Lewis. NB4 is similar to NA4 in that it also uses the quasi-normalized kurtosis given in equation 2 above. The major difference is that instead of using a residual signal, NB4 uses the envelope of the signal bandpassed about the mesh frequency. As with the other demodulation techniques, the signal is band-passed filtered about the dominant (primary) meshing frequency. Using the Hilbert transform, a complex time signal is created in which the real part is the band-pass signal, and the imaginary part is the Hilbert transform of the signal. The envelope is the magnitude of this complex time signal, and represents an estimate of the amplitude modulation present in the signal due to the sidebands. Amplitude modulation in a signal is most often due to transient variations in the loading. The basic theory behind this method is that a few damaged teeth will cause transient load fluctuations unlike the normal tooth load fluctuations, and thus be observed in the envelope of the signal. NB4 can be calculated using equation 2 above, with the exception of substituting the envelope of the signal in place of the residual signal. NB4* uses the same modification technique as NA4*. NB4 is also dimensionless, with a value of 3 under nominal conditions.

Apparatus and Gear Damage Review: The fatigue damage on the test pinion shown in figures 1 through 8, was obtained using the spiral bevel gear fatigue test rig illustrated in figure 9, at NASA Lewis Research Center. The primary purpose of this rig is to study the effects of gear tooth design, gear materials, and lubrication types on the fatigue strength of aircraft quality gears. Because spiral bevel gears are used extensively in helicopter transmissions to transfer power between nonparallel intersecting shafts, the use of this fatigue rig for diagnostics studies is extremely practical. Vibration data from an accelerometer mounted on the pinion shaft bearing housing was captured using an on-line program running on a personal computer with an analog to digital conversion board and anti-aliasing filter. The 12-tooth test pinion, and the 36-tooth gear have a 35 degree spiral angle, a 1 in. face width, a 90 degree shaft angle, and a 22.5 degree pressure angle. The pinion transmits 720 hp, at a nominal speed of 14,400 rpm.

Pictures of tooth damage on the pinion at various stages in the test are illustrated in figures 1 through 8. At the first rig shut-down, at about five and a half hours into the test, a small pit was observed on one of the teeth on the test pinion, as illustrated in figure 1. The rig was shut-down an additional seven times to observe and document the damage as it progressed during the run. As seen in figures 2 through 4, the pitted area gradually spread to cover over 75% of the face of pinion tooth. At

4

approximately twelve hours into the run, pitting started to appear on adjacent teeth, as seen in figure 5. The pitting on the adjacent teeth continued to grow until it covered a majority of the face of three adjacent teeth on the pinion, and part of the face on another adjacent tooth, as seen in figure 7, taken at approximately sixteen hours into the run. The run was stopped when it was found that one of the three heavily pitted pinion teeth experienced a tooth fracture, losing one third of the tooth, as illustrated in figure 8. The break-off occurred sometime between the seventh shut-down (16.16 hours) and the end of the test (17.79 hours).

Discussion of Results: Figures 10 and 11 illustrate the minor speed and load fluctuations present during the run. Figures 12 through 20 illustrate the results of applying the various fault detection methods to the experimentally obtained vibration data. In all of the figures from 10 through 20, the vertical dashed lines numbered 1 through 8 correspond to the eight rig shut-down times, with the resulting damage documented in figures 1 through 8, respectively.

The fluctuations in speed and load over the course of the run were found to have significant effects on the response of the fault detection techniques. As seen in figure 10, the rig speed varied within a band of approximately 6% about the nominal pinion speed of 14,400 rpm. From figure 11, it also can be seen that the gear torque varied within a band of approximately 18%. The sharp change in speed and load that occurred at approximately 8.75 hours into the run, shortly after shut-down #3, affected the response of all of the parameters, in particular NA4. As seen in figure 15, the response from NA4, and NA4*, more than doubled, not due to a major increase in damage, but to the load and speed change at that point. The step changes in speed following shut-downs 4, 5, and 6, and the gradual change in speed in the interims between shut down are clearly evident in a majority of the parameters. The various levels of parameter response for FM0, FM4, NA4, and NB4, as seen in figures 12, 14, 15, and 16, respectively, can be directly linked to the speed changes. The sudden drop in parameters NA4 and NB4 at approximately 3.75 hours, as seen in figure 13, corresponds exactly to the shift in gear torque at that time, as shown in figure 11.

As seen in figure 12, the parameter FM0 shows only moderate changes as the damage starts and progresses. A majority of the variations in FM0 are most probably due to the speed and load variations during the run.

Parameters NA4 and NB4 are the first to react to the pinion tooth damage, as seen in the first 6.5 hours comparison plot of NA4, NB4, and FM4, illustrated in figure 13. The damage observed during shut-down number 1, illustrated in figure 1, occurred sometime between the start of the run and the time of the first shut-down, 5.50 hours. In earlier studies, parameter NA4 was shown to be very reliable and sensitive to the start of pitting damage [6]. At approximately 1.25 hours into the run both NA4 and NB4 increase from the nominal value of 3 to values from 4 to 6, thus indicating the start of tooth damage. Both NA4 and NB4 drop in amplitude at approximately 3.75 hours, coincident with, and thus influenced by, the change in gear torque that remains until the first shut-down (5.5 hours).

Parameter FM4 did show a possible reaction to the pit at approximately 3 hours into the run, as illustrated in figure 14. FM4, however, gives no coherent indication as the pitting grows in severity, even when it is still limited to a single tooth, i.e. up to approximately 10 hours into the run. This is surprising since FM4 was designed to be a single tooth defect parameter. Most of the changes seen in FM4 are due to corresponding load and speed changes.

As seen in figure 15, NA4 not only gives an initial reaction to damage at 1.25 hours, but it also continues to react as the damage increases. When the rig is restarted after shut-down #1, NA4 increases steadily to a value of 7, as the damage progresses from the small pit in figure 1, to the pit

seen in figure 2, (covering 50% of the tooth). NA4 then continues to increase to a value of 17, as the pit grows to cover over 75% of the tooth surface, as illustrated in figure 3. NA4 then progressively drops down, as its run averaged denominator increases. NA4* maintains its sensitivity, due to the denominator being locked, and thus continuing the comparison of current conditions to the denominator representing the system in "good" condition. Again, the speed and torque influences on parameters NA4 and NA4* are clearly seen, especially near shut-downs 3, 4, and 5.

Parameter NB4 shows trends very similar to those seen in NA4, except NB4 gives a more robust reaction to the damage. As seen in figure 16, NB4 increases from a value of 5 for the observed small pit, figure 1, to a value of 25, as the pit covers 50% of the tooth, figure 2. When the pitting covers over 75% of the tooth, figure 3, NB4 increases to a value of 40. As with parameter NA4*, NB4* is used to maintain the response through the end of the test. Again, the speed and load variations clearly affect the response of parameter NB4 and NB4*, as seen in figure 16, near rig shut-downs 3, 4, 5, and 6.

Figures 17 and 18 present the results of computing the standard deviation of the instantaneous frequency (I.F.) of the bandpassed signal using ± 2 sidebands, and ± 1 sideband, respectively. As seen in figure 17, the I.F. gives a robust reaction once the pitting is established, at 5.5 hours. This reaction is coincident with the start-up of the rig, following shut-down #1. However, neither the speed nor load change sufficiently enough at the start-up to cause the I.F.'s initial and sustained reaction at that point. Unfortunately, the ultra-sensitivity of this parameter makes it vulnerable to noise in the signal, even though the noise has been minimized with time synchronous averaging. Because the gear ratio of the test mesh is exactly 3:1, it is nearly impossible to remove the gear vibration from the pinion vibration signal. Some of the noise in the results shown in figure 17 could be due to the combination of gear noise in the signal, and the increased sensitivity of the parameter. Reducing the number of sidebands used to only ± 1, in an effort to reduce noise in the signal, results in eliminating some of the fault information from the signal, as illustrated in figure 18.

The standard deviation of the instantaneous phase (I.P.) is illustrated in figure 19. As seen in this figure, the I.P. gives a robust reaction at 5.5 hours into the run, after the pit has been established. The I.P. increases as the pit grows to cover over 75% of the tooth face, similar to NA4 and NB4, however in a less steady manner. The I.P. continues to react to the end of the test, fluctuating in some cases as a result of the speed changes. It is not known why the I.P. gave no clear reaction to the pitting prior to 5.5 hours into the run.

Figure 20 shows the denominator of parameter NB4, or the run averaged variance of the envelope of the bandpassed signal. Due to the run averaging process, this parameter increases steadily as the pit grows from the initial small pit to the end of the test. It gives a steady indication of accumulative damage without the influence of speed or load fluctuations.

Based on the results just presented, parameters NA4 and NB4 gave the best indication of the start and initial progression of pitting damage. As discussed, NA4 and NB4 detected tooth damage at approximately 1.25 hours into the run, which was the first indication of all the methods investigated. NA4 and NB4 continued to increase as the pitting damage increased to cover over 75% of the pinion tooth.

An unexpected result of this study showed that although the speed of the rig was held to a band within six percent of nominal speed, and the load was held to within a band of eighteen percent of nominal, the resulting speed and load variations present during the test substantially affected the performance of all the gear fault detection techniques investigated. To increase the reliability of the

parameters over speed and load variations, the more promising parameters, NA4 and NB4, should be modified to adapt to the different load and speed baselines to give consistent values based on damage alone, regardless of operating conditions.

Conclusions: Based on the results of applying a number of gear fault detection techniques to experimental data from a spiral bevel gear fatigue rig, the following conclusions can be made;

1) Parameters NA4 and NB4 were the first to react to the gear surface damage, and thus are good indicators of initial pitting.
2) Parameters NA4 and NB4 continued to react as the surface pitting increased to cover over 75% of the face width of the pinion, thus indicating increasing damage severity.
3) The run-normalized variance of the bandpassed signal's envelope (denominator of NB4) was found to be a good accumulative damage indicator.
4) The standard deviation of the instantaneous phase and instantaneous frequency gave robust indications of the pitting damage, once the pitting was established. These parameters, however, are more sensitive to noise in the signal.
5) All of the methods were sensitive to the minor changes in rig speed and load. Additional research is needed to modify methods, such as NA4 and NB4, to give reliable indications, regardless of speed and load.

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Figure 1.—Pinion damage at t = 5.50 hr.

Figure 2.—Pinion damage at t = 6.55 hr.

Figure 3.—Pinion damage at t = 8.55 hr.

Figure 4.—Pinion damage at t = 10.03 hr.
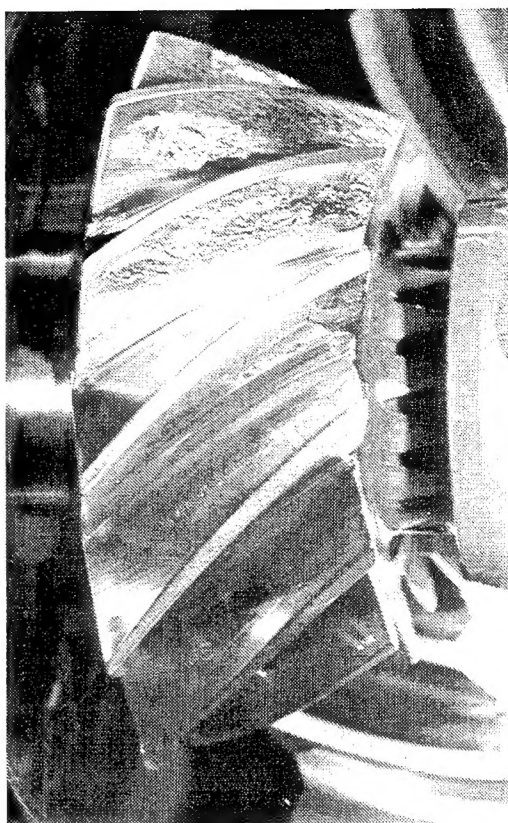
Figure 5.—Pinion damage at t = 12.03 hr.

Figure 6.—Pinion damage at t = 14.53 hr.
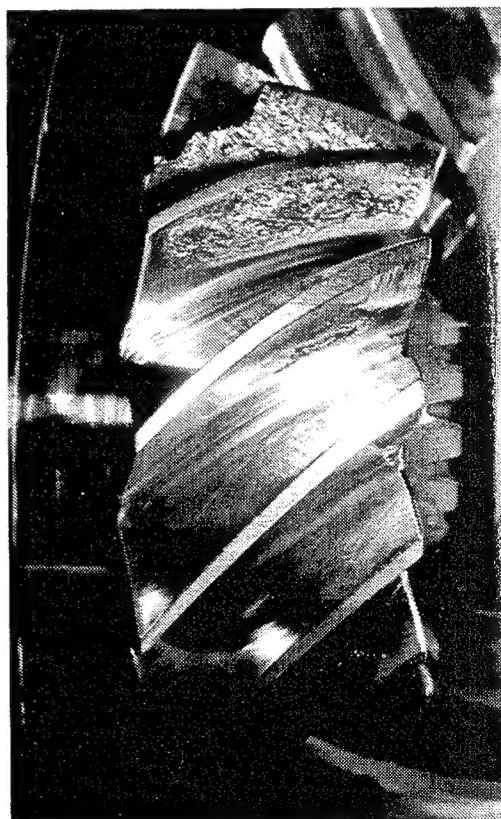

Figure 7.—Pinion damage at t = 16.16 hr.
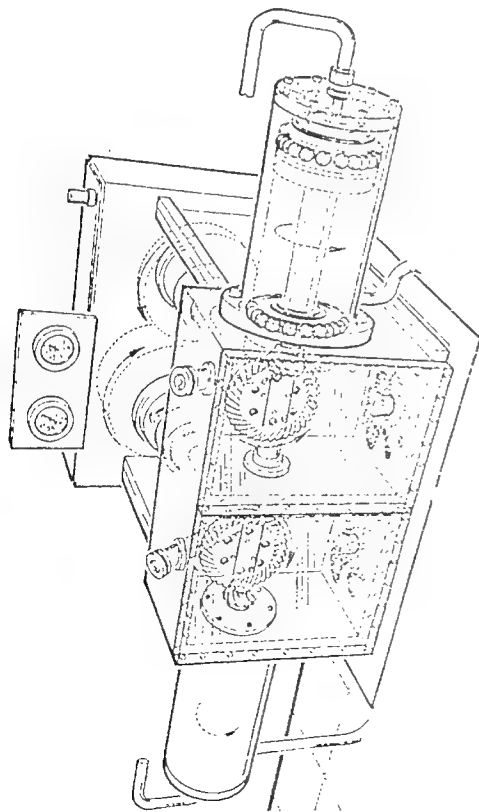

Figure 8.—Pinion damage at t = 17.79 hr (end).

Figure 10.—Rig speed-vs.-run time.

Figure 12.—Parameter FM0-vs.-run time.

Figure 9.—Spiral bevel gear fatigue test rig at NASA Lewis.

Figure 11.—Torque on gear-vs.-run time.
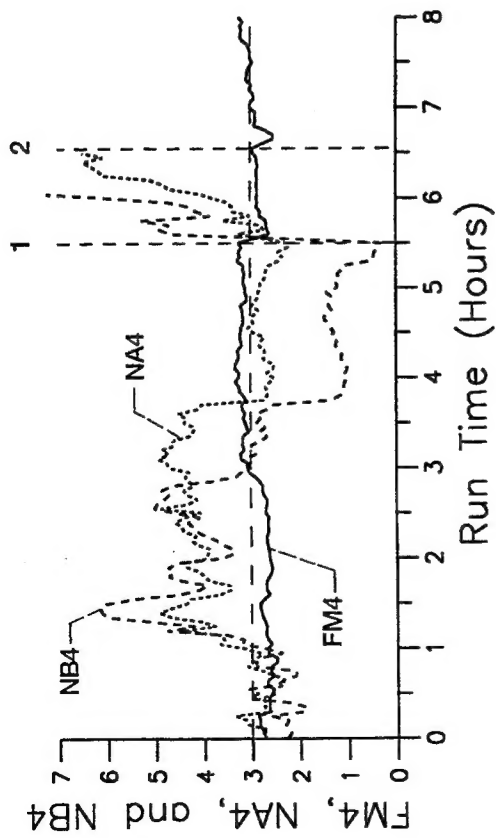
Figure 13.—Comparison of parameters FM4, NA4, and NB4 over first 8 hrs.
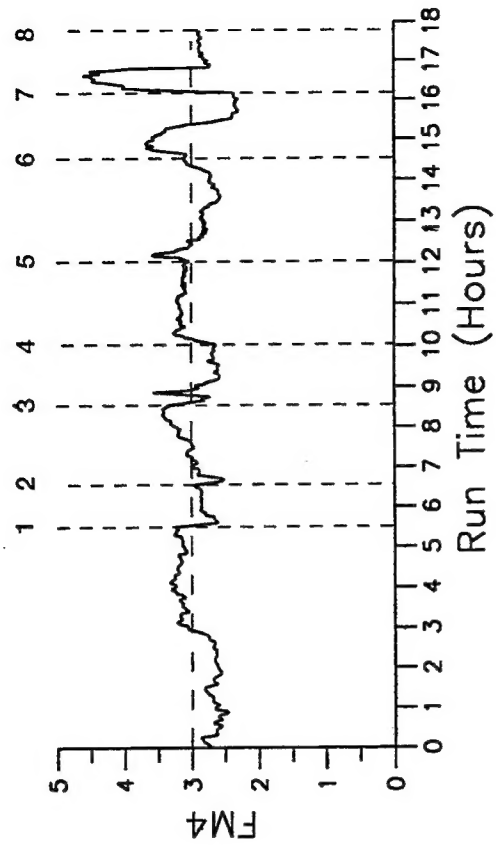
Figure 14.—Parameter FM4-vs.-run time.
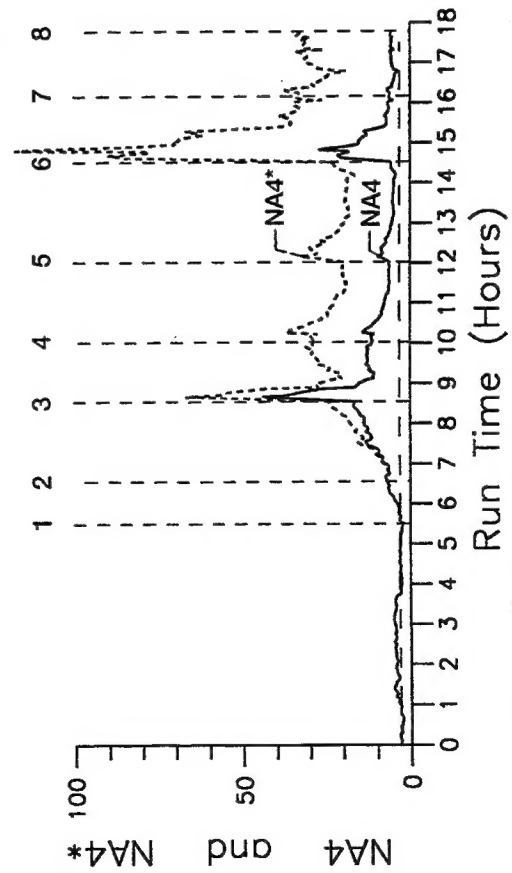
Figure 15.—Parameters NA4 and NA4*-vs.-run time.
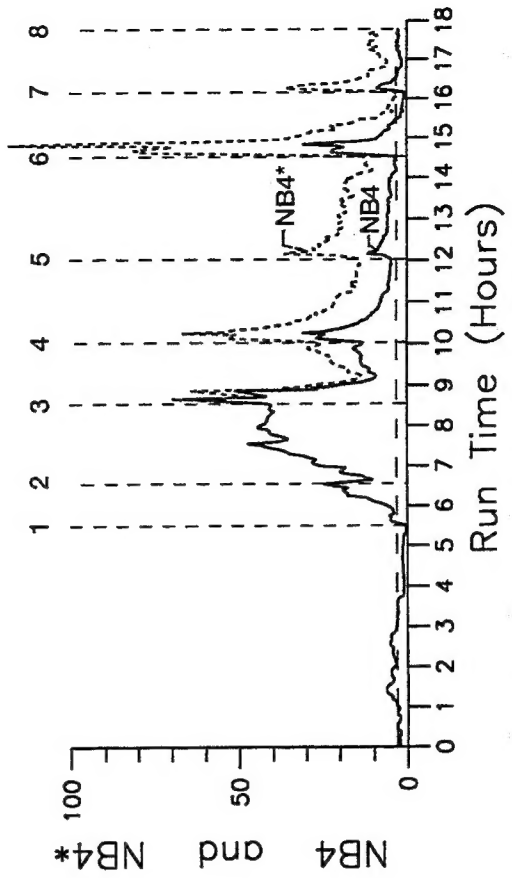
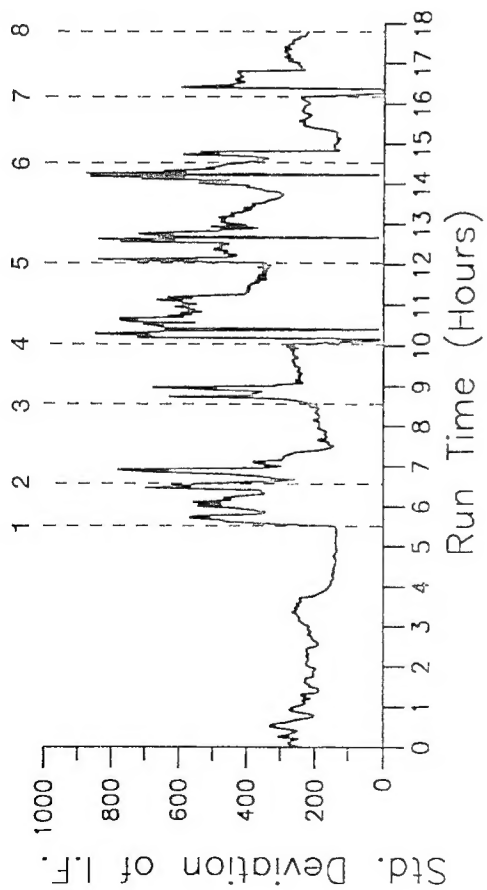Figure 16.—Parameters NB4 and NB4*-vs.-run time.

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Figure 17.—Standard deviation of instantaneous frequency (with ±2 sidebands).
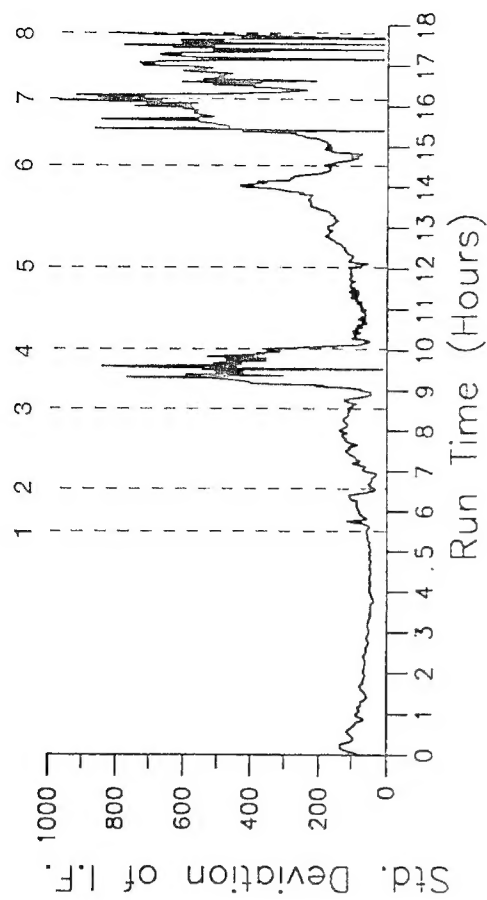

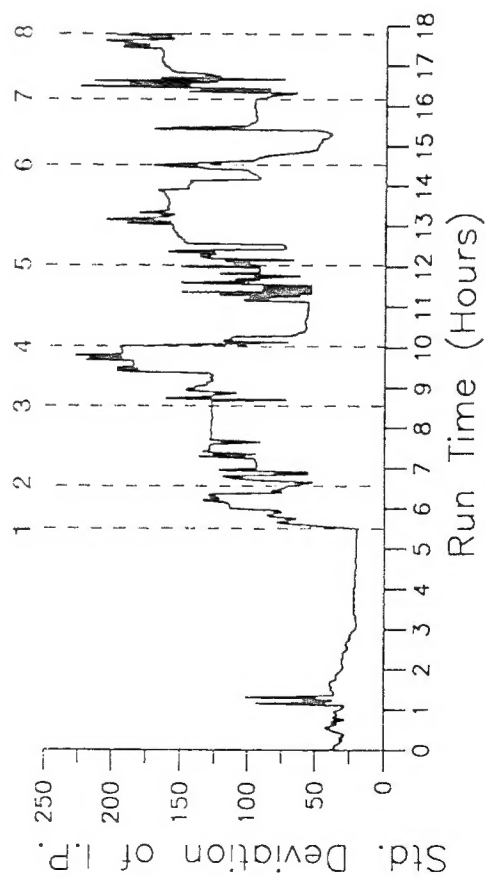Figure 18.—Standard deviation of instantaneous frequency (with ±1 sidebands).

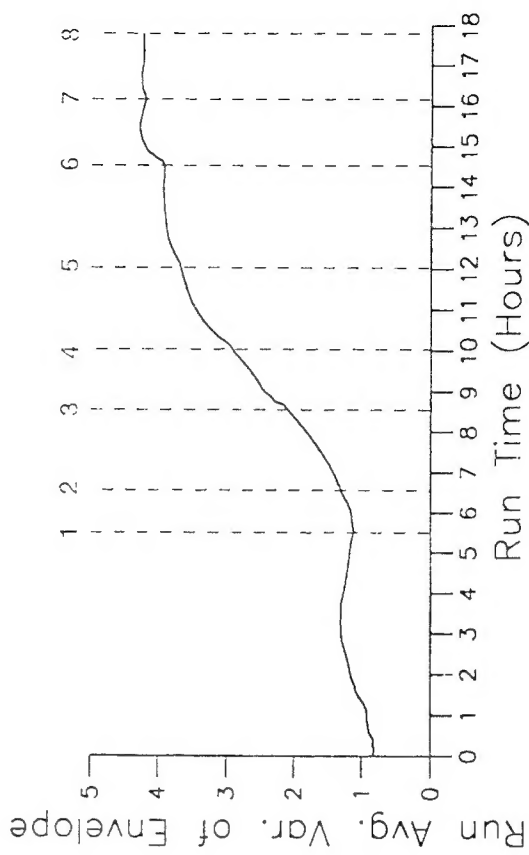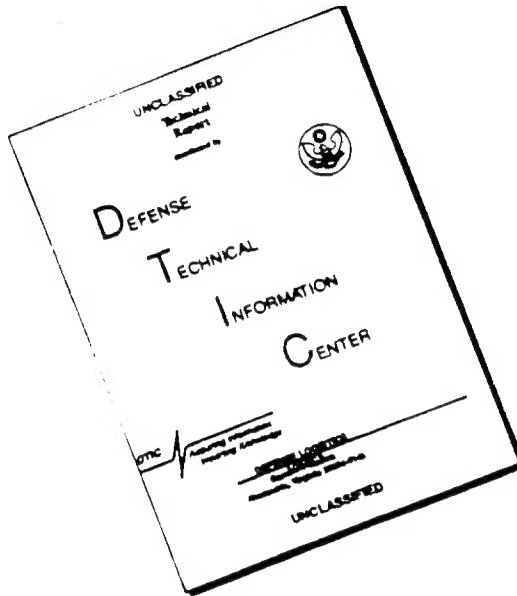Figure 19.—Standard deviation of instantaneous phase-vs.-run time.

Figure 20.—Denominator of parameter NB4-vs.-run time.

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13. ABSTRACT (Maximum 200 words)

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